Ultracompact Monolithic Integration of Balanced, Polarization Diversity Photodetectors for Coherent Lightwave Receivers

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Abstract—**We monolithically integrate an optical front-end on InP for balanced, polarization-diversity coherent lightwave reception which is only 1.3 mm long. Low on-chip insertion loss (< 4.5 dB) and balanced photoresponse (1.05:1 or better) are achieved at 1.5 μm wavelength using straightforward, regrowth-free fabrication. Low capacitance photodetectors ($\leq$ 0.15 pF) are employed for high bandwidth operation.**

MONOLITHIC integration of optical waveguide devices with other optoelectronics enhances on-chip functionality, and improves packaging cost and reliability by minimizing hybrid optical interconnections. A target application for such integration has been coherent lightwave receiver front-ends, combining photodetectors with 3 dB waveguide couplers for balanced operation [1]–[6] and polarization-splitting optics for polarization-insensitive reception using diversity architectures [5], [6]. Compatibility with high III-V materials' cost, however, requires high-yield integration processes and compact device size. The large size, typically several millimeters, of waveguide couplers with associated input–output branching is a serious obstacle to cost-effective monolithic integration. We previously reported alternative approaches for ultra-compact 3 dB couplers [7] and polarization-selective detectors [8]. Here we integrate both device types on a single InP chip to realize an ultracompact (1.3 × 0.4 mm^2), balanced, polarization-diversity photodetector which is easy to fabricate (no epitaxial regrowth, minimal photolithography) and exhibits low detector capacitance (< 0.15 pF).

Our device (Fig. 1) consists of two single-mode input rib waveguides for photosignal and local oscillator (LO) inputs, a multi-mode interference [9] (MMI) 3 dB coupler formed by circular bends branching into and out of a zero-gap coupling region, and dual polarization-selective coupler/photodiode pairs for detection of the 3 dB coupler outputs. The input guides are InGaAsP(λ_g = 1.1 μm):Fe/InP:Fe double-heterostructures with 0.53 μm core, 1 μm upper cladding, and 3 μm rib width. The 3 dB coupler employs an 8 × 298 μm interference region. Its key features are large input guide separation (250 μm) for ease of fiber coupling, intrinsic MMI polarization-insensitivity [7], and 250 μm bend radii for ultracompact size (840 μm). Low bend radiation loss is achieved by etching the guide ribs well below the waveguide core (5 μm rib height). This design eliminates difficult lithographic definition of the gap [1], [2], [6] or Y-junction [3] in conventional directional couplers. MMI coupler outputs are laterally uptapered over 177 μm to reduce diffraction in the following planar waveguide circuit. The tapers launch light into polarization-selective detectors, consisting of vertically defined planar waveguide couplers integrated with mesa p-i-n photodiodes [8]. Couplers nearest the MMI device are covered with gold to phase mismatch the TM polarization, so that only TE-polarized light is coupled into the first photodiode; the second coupler/diode pair collects the remaining TM light. The two detectors corresponding to each polarization state are interconnected for on-chip photocurrent subtraction (Fig. 2), which is essential for broadband, balanced operation without microwave hybrids [4]. Key features are short length (< 300 μm), small diode area (20 × 28 μm^2 TE, 34 × 28 μm^2 TM) for low capacitance, and semi-insulating guide layers for on-chip current subtraction. The n$^+$-InGaAsP layer serves both as a low resistance diode contact and as an optical "impedance matching" layer to enhance guide-detector coupling [10]. The vertical coupler design eliminates all critical lithography for these devices.

Fabrication is straightforward, involving a single epitaxial growth by low-pressure organo-metallic chemical vapor deposition on a planar InP:Fe substrate, followed by conventional processing with minimal coupler lithography. The process sequence is i) p-i-n diode fabrication and Au vertical coupler metallization [8], ii) Ti/Au diode interconnect metallization, iii) vertical coupler length definition, and iv) MMI coupler definition (chemically assisted reactive ion beam etching through a resist mask). We use

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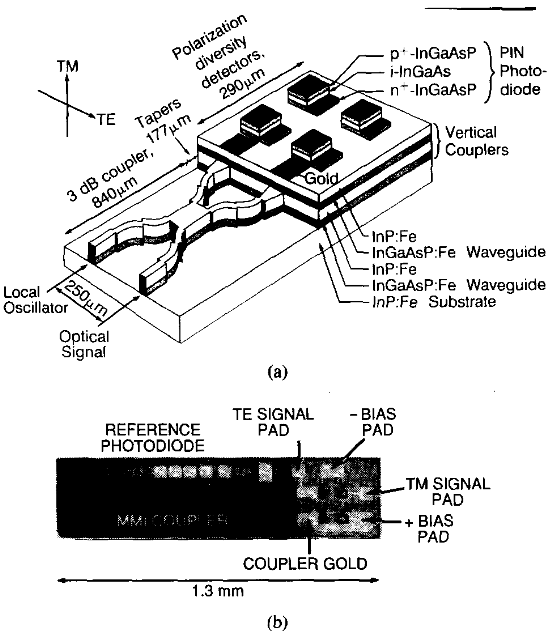

Fig. 1. (a) Device schematic. Diode passivation, interconnect and bond pads are not shown. (b) Optical micrograph of chip, including 600 μm reference photodetector.

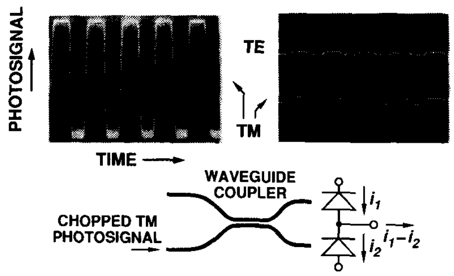

Fig. 2. Balanced operation with on-chip current subtraction. Photodiode signals from a single TM diode i_1 (left) and for both balanced pairs $i_1 - i_2$ (right) for TM input polarization {0.1 V, 2 ms per division}. Bottom shows measurement conditions and on-chip interconnections for a *single* balanced diode pair (second pair not shown).

epitaxially grown p^+-i junctions to avoid diffusion or implantation, and fully cured (315°C, 60 min) polyimide for diode passivation. All etching except step iv) above employs selective wet chemistry. Multilayer contact lithography [11] is used for accurate guide definition on the nonplanar wafer in step iv); projection lithography would allow a single-layer process. Notably, monolithic coupler integration does not appreciably complicate fabrication, as compared to the balanced photodiode arrays without couplers required for hybrid integration of coherent receivers [12, 13]. Coupler integration adds only three additional lithographic levels and no epitaxial regrowth. Our 1.3 mm chip length is comparable to the ≈ 1 mm length of linear 4-detector arrays without couplers [14] required for hybrid receivers.

Measured diode capacitances are 100 (140) fF at -4 V bias for TE (TM) detectors. These values are limited by a thin i-layer (1 μm), which could be increased for at least two-fold capacitance reduction. A systematic 10 fF capacitance difference associated with interconnect asymmetry was observed within each balanced pair, similar to that reported for diode arrays without couplers [12]. A diode series resistance $\approx 20\ \Omega$ was determined from S-parameter data. The larger TM detectors exhibit a 12–13 GHz bandwidth into 50 Ω under waveguide illumination at $\lambda = 1.5$ μm, as determined with on-wafer microwave probes. Preliminary measurements show that the bandwidth remains above 5 GHz up to optical intensities corresponding to 500 μA photocurrent. Photodiode dark currents (8–10 nA at -4 V) are acceptable for coherent reception, where ≈ 1 mA LO photocurrents are expected. A linear variation of dark current with reverse bias suggests that it is due to finite epilayer sheet resistance rather than p-n junction leakage.

The devices were evaluated at $\lambda = 1523$ nm using objective lens or fiber input coupling. The propagation loss of straight waveguides on the chip is 1.1 dB/cm, determined by Fabry–Perot techniques [15]. Optical attenuation in excess of straight guide insertion loss was determined by comparing detector quantum efficiencies for the complete detectors to 600 μm-long reference waveguide detectors fabricated on the same chip (assumed to collect all guided light), and to polarization-sensitive detectors without 3 dB couplers. On-chip losses for TE (TM) light were 1.5 (4.4) dB, of which 0 (2.0) dB result from MMI coupler integration. The measured coupling loss from conical-tip fiber pigtails to devices without antireflection (AR) coatings was 2.3 dB, of which 1.5 dB is due to Fresnel reflection. Thus, we expect 2.3 (5.2) dB total insertion loss for conversion of TE (TM) optical power in the fiber to detector photocurrents using AR-coated chips. This loss is comparable to that of a recently reported hybrid coherent receiver [13].

Our MMI coupler's polarization dependence is much stronger than that of earlier devices [7] due to three factors: i) nonideal fabrication, resulting in fundamental mode loss (conversion to higher-order, substrate-leaky modes) for *both* polarizations, ii) reduced substrate leakage due to the very deep rib etch so that light from all modes reaches the vertical couplers, and iii) increased diffraction loss of higher-order TM modes in the vertical couplers due to the larger TM detector-to-MMI coupler separation. The multimode character of optical near-field patterns at coupler/taper outputs after cleaving away the vertical couplers supports this interpretation. Therefore, MMI coupler optimization should result in 1 dB TM-TE loss difference.

Balanced operation was verified by measuring the photocurrents i_1, i_2 flowing in each photodetector and $i_1 - i_2$ at the intermediate frequency (IF) output with only one optical input (Fig. 2), using optical input intensities to provide $i_1 = 50$ to 200 μA. Typical balance was $i_1/i_2 = 1.05$ for both polarizations, corresponding to a low-

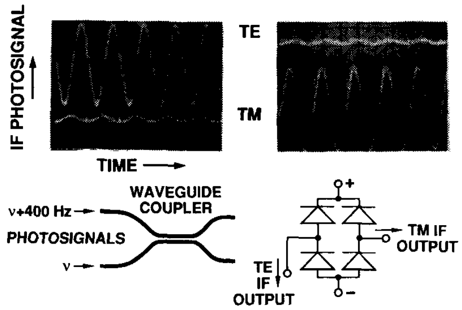

Fig. 3. Polarization selectivity. Photos show the two 400 Hz IF signals when both optical inputs are aligned to TE (left) or TM (right polarization {0.3 V, 2 ms per division}, for the TE (upper) and TM (lower trace) detectors. Extinction ratios define the maximum/minimum photosignal ratio for a given detector. Bottom shows measurement conditions and complete on-chip interconnections.

frequency common-mode rejection ratio of 26 dB (electrical) for LO intensity noise. The best devices exhibit 33–37 dB of CMRR. These compare favorably with other reported monolithic waveguide circuits [1]–[3], [5] and some hybrids [13] (CMRR $\leq$ 16 dB), and approach the best hybrid receivers (40 dB) [12]. The relative IF phases and polarization selectivity were determined using two optical inputs with 400 Hz frequency difference (Fig. 3), generated from a single laser source (self-heterodyne) [16]. The phase difference between the beat signals generated in each photodiode within a pair was the ideal 180° value within our $\pm 5°$ uncertainty, as determined from simultaneous observation of photocurrents at both bias contacts. The polarization extinction of beat signals at the IF outputs was 12.7 (11.9) dB for the TE (TM) branch (Fig. 3). This selectivity should result in < 1 dB IF power variation due to polarization fluctuations in a diversity receiver with perfect square-law demodulators [17]. Even better selectivity (≥ 15 dB) is anticipated from coupler optimization [8]. Devices with and without 3 dB couplers show identical extinction, indicating that the 3 dB coupler does not affect polarization selectivity.

In summary, we have demonstrated ultracompact, monolithic integration of a balanced, polarization diversity photodetector. Our simple, regrowth-free integration approach minimizes lithographic difficulties inherent in coupler definition, which can be severe when detector integration introduces nonplanar topography. Thus, this work shows that appreciable optical signal processing can be incorporated with photodetectors *without compromising chip size or ease of fabrication.* Our compact optical design should also result in a broad spectral operating range (≈ 70 nm) [7], [8]. We anticipate that our integration approach will prove widely applicable to advanced lightwave receivers for both wavelength-multiplexed (direct) and coherent detection. For example, replacing the 2×2 3 dB coupler used here with a 2×4 MMI device described elsewhere [16] could lead to ultracompact (≈ 2 mm), balanced polarization-diversity photodetectors for image-rejection or phase-diversity coherent detection.

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